Zero temperature phase structure of multi-flavor QCD*

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To study continuum limit of lattice QCD with many light quark flavors, we investigate the zero temperature phase structures of multi-flavor QCD. Currently a series of exploratory simulations are being performed with the number of quark flavors, N_f= 6, 8, and 10 on a set of lattice volumes for various quark masses. Here, we report on the current status of our simulation on a 8^4 lattice.

1. Introduction

Perturbative analysis of QCD coupling constant renormalization tells us that the coefficients in the series expansion of the β-function changes their signs depending on the number of light quark flavors. Based on this, it was suggested that long and/or short distance behavior of QCD may change with the number of light quark flavors [1]. Although these arguments are founded upon perturbation theory, they may remain valid even in the non-perturbative regime. Indeed, lattice simulations with multi-flavored QCD reveal rich phase structures[2–4].

For eight light staggered quark flavors, there is a strong first order phase transition which separates the strong coupling region from the weak coupling region. For a given lattice spatial volume, this transition appears to be N_t-independent bulk transition where N_t is the number of sites along the time direction. The weak coupling phase is divided into two region : in one region of weak coupling space chiral condensates shows linear behavior in quark mass, and in the other region they show non-linearity[3]. It has been speculated that there may be a normal finite temperature phase transition between these two different weak coupling phases. On the other hand, using simulation results with Wilson quark formulation in the strong coupling limit, the authors of Ref. [4] argue that lattice QCD for $N_f \geq 7$ has an interacting limit without quark confinement in contrast to the usual QCD, a theory with spontaneous chiral symmetry breaking and color confinement in low energy. Even if the color confinement and the spontaneous chiral symmetry breaking is rigorously proven in the infinite coupling limit (in quenched approximation to QCD), it is claimed that copious addition of light quark flavors modifies the string-like vacuum structure of a theory with gluon only.

In short, the existence of a strong first order bulk phase transition which separates the strong coupling region and the weak coupling one is well established. Continuum limit of lattice theory for multi-flavor QCD is less clear. For staggered quark simulations, investigation of the weak coupling phase by use of hadron spectroscopy calculation was hampered by small spatial lattice volumes [3]. Simulation result with Wilson dynamical quark in the strong coupling limit is difficult to make a contact with the continuum limit. Thus, further study in the weak coupling phase structure of multi-flavor QCD using light dynamical quarks is needed. Here, we would like to endeavor toward this direction. Our efforts will be concentrated on various susceptibilities such as chiral susceptibility and finite size scaling of them.

2. Simulation Characteristics

We use R-algorithm[5] to simulate QCD with arbitrary number of quark flavors and employ

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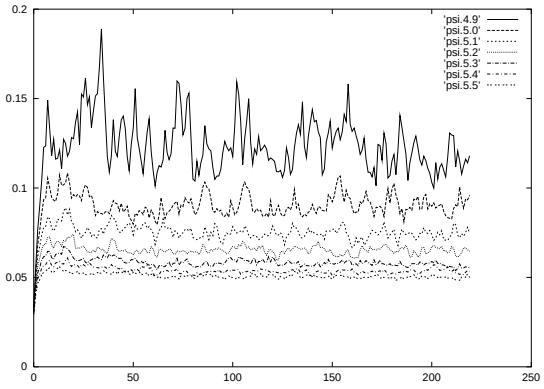

Figure 1. Monte Carlo time evolution of chiral condensate for $N_f = 6$ with $m_q a = 0.01$.

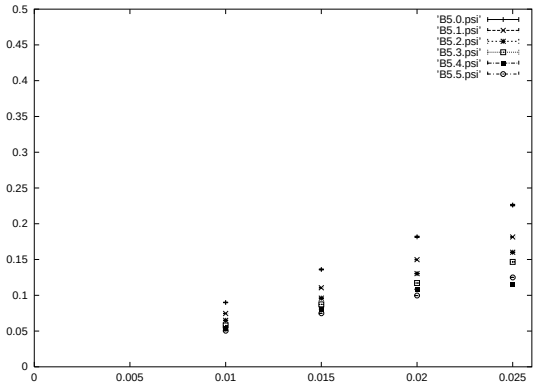

Figure 2. Chiral condensate for $N_f = 6$ vs $m_q a = 0.01, 0.015, 0.02, 0.025$ at different β's

staggered fermion method for the dynamical quarks. Target platform for our project is 128-node Fujitsu VPP-700 at RIKEN, the Institute of Physical and Chemical Research, in Japan. Since we expect the need for large lattice volume from other groups' experiences, two dimensional layout of compute nodes is adopted as part of our parallelization strategy. Similar to our work on quenched spectroscopy of QCD[6], four dimensional $N_t \times N_x \times N_y \times N_z$ lattice points are distributed evenly over the y and the z directions so that for given number of compute nodes, it is divided into $M_y \times M_z$'s y directional and z directional nodes. Each compute nodes handles $N_t \times N_x \times L_y \times L_z$ sub-lattice points. For example, 8^4 lattice volume run reported here uses 8-node partition. This 8-node partition is layed out as $(4, 2)$ mesh points and each nodes computes $8{\times}8{\times}2{\times}4$ sub-lattice points. We also use checkerboarded site classification for storing dynamical variables. Periodic boundary condition for the time direction is imposed on the gauge field. Anti-periodic boundary condition for the time direction is imposed on the fermion. For the three space directions, periodic boundary condition is used for all fields. Before studying zero temperature phase structure of multi-flavor QCD in detail, a set of exploratory runs on a 8^4 lattice with time step $\Delta\tau = 0.01$ was done. Simulations with dynamical quark mass $m_q a = 0.01, 0.015, 0.02$, and 0.025 is performed for the number of quark flavors, $N_f = 6$ and 8. Since we are interested in the weak coupling phase, range of $\beta = 6/g^2$ from 5.0 to 5.5 is chosen for the preliminary run (note that for a 16^4 lattice volume with $N_f = 8$ staggered quarks, the critical coupling is 4.62(1) for $\Delta\tau = 0.005$[3]). There is $(\Delta\tau)^2$ errors associated with R-algorithm and the difference in the step size makes quantitative comparison more subtle.

Figure 1 shows typical Monte Carlo evolutions of the chiral condensate for four different quark masses with $N_f = 6$ at each β. Ordered start runs with total simulation time, $\tau \sim 220$, are shown in the figure. The average values of the chiral condensate from the Monte Carlo time $\tau = 20$ to $\tau = 220$ are given in Figure 3. The error in the figure does not include auto-correlation among the data and are probably underestimated. There is a linear relationship between the chiral condensate and the quark mass and it is in agreement with

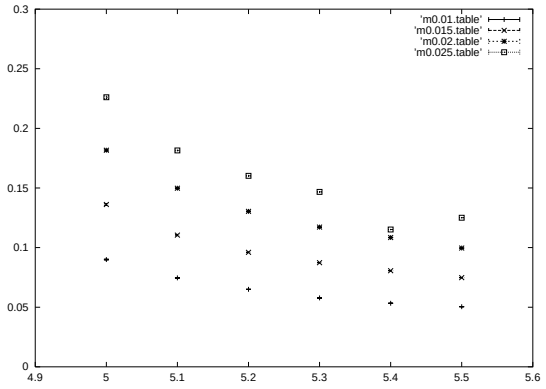

Figure 3. Chiral condensate for $N_f = 6$ for each $m_q a$ at different coupling constant, $\beta = 6/g^2$

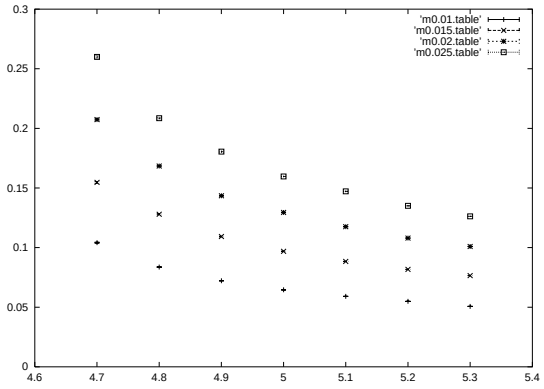

Figure 4. Chiral condensate for $N_f = 8$ for each $m_q a$ at different coupling constant, $\beta = 6/g^2$

the behavior found in [3]. Similarly, the average chiral condensate for $N_f = 8$ is shown in Figure 4. The simulation length, τ, is ~ 220 and the average is over the last $\tau = 200$ time unit. Ranges of $\beta = 4.7 \sim 5.5$ are simulated with the same set of quark masses as $N_f = 6$.

3. Discussion

In order to study the zero temperature behavior of multi-flavor QCD further, we started full dynamical simulation. R-algorithm which allows us to simulate arbitrary number of quark flavors is chosen. Our simulation is at early stage of investigation and is currently compared with earlier results by other groups on a small 8^4 lattice volume. The weak coupling phase of $N_f = 6$ and 8 is investigated. There exist a linear relation between the chiral condensate and the light dynamical quark mass, which is in agreement with earlier results. For the planned more detailed investigation of the weak coupling phase, several aspects of the current lattice calculation need to be refined. First, we need to test whether $\Delta\tau^2$ error associated with the current algorithm is small in the simulation result. Next, we need to add more observables : various susceptibilities such as chiral susceptibility calculation and specific heat calculation are currently being implemented.

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